NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

TECHNICAL NOTE

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WIND-TUNNEL INVESTIGATION OF THE NACA 65_4-421 AIRFOIL SECTION WITH A DOUBLE SLOTTED FLAP AND BOUNDARY-LAYER CONTROL BY SUCTION

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SUMMARY

An investigation has been conducted in the Langley two-dimensional low-turbulence tunnel to find the effects of boundary-layer control on the aerodynamic characteristics of the NACA 65_4-421 airfoil section with a boundary-layer-control suction slot at 0.45 airfoil chord and a 0.32-airfoil-chord double slotted flap. This airfoil is designed primarily to obtain a high maximum lift coefficient. The tests consisted of lift measurements with the flap deflected and lift and drag measurements with the flap retracted over a range of flow coefficient from 0 to 0.03 for the model smooth and rough at Reynolds numbers of 1.0×10^6 and 2.2×10^6. The flow coefficient is defined as the ratio of the quantity rate of air flow removed through the suction slot to the product of the wing area and the free-stream velocity.

Greater increases in the maximum lift coefficient through boundary-layer control were obtained with the flap retracted than with the flap deflected and with the smooth model than with the model with leading-edge roughness. In the smooth condition at a Reynolds number of 2.2×10^6, increasing the flow coefficient from 0 to 0.015 increased the maximum lift coefficient from 1.22 to 2.43 with the flap retracted and from 3.07 to 3.81 with the flap deflected. Little increase in maximum lift was obtained with the flap deflected between flow coefficients of 0.015 and 0.030. In general, between Reynolds numbers of 1.0×10^6 and 2.2×10^6, for the range of flow coefficient investigated, increasing the Reynolds number tended to increase the maximum lift coefficient below a flow coefficient of 0.015 and to decrease the maximum lift coefficient between flow coefficients of 0.015 and 0.030. With the flap retracted, increasing the flow coefficient decreased the minimum section drag coefficient and maintained low drag coefficients to high lift coefficients. The drag coefficients equivalent to the boundary-layer-control power were greater, however, than the reduction obtained, at least over the range of lift coefficient for which the drag was measured without boundary-layer control.

INTRODUCTION

It has been established that by sucking low-energy air from the thick turbulent boundary layer or by blowing high-energy air into it, separation of the flow from an airfoil surface may be delayed and the maximum lift may be increased. As part of a research program to investigate airfoil configurations that would utilize boundary-layer suction to produce high maximum lift coefficients, investigations have been reported in references 1 and 2 for NACA 6-series airfoils having thickness-chord ratios of 0.12 and 0.18, respectively, with boundary-layer suction in conjunction with other high-lift devices. The present investigation is an extension of this work and was made with the NACA 65_4-421 airfoil section incorporating a boundary-layer suction slot at 0.45 airfoil chord and a 0.32-airfoil-chord double slotted flap. This suction-slot location was selected as likely to be most effective in increasing the maximum lift coefficient.

The tests were conducted in the Langley two-dimensional low-turbulence tunnel at Reynolds numbers of 1.0×10^6 and 2.2×10^6. Lift measurements were made for various suction quantities both with and without leading-edge roughness with the double slotted flap at its optimum position and deflection. The lift and drag characteristics of the airfoil were similarly determined for the flap-retracted position. Measurements of the total pressure loss in the suction system were made in order to estimate the power required for boundary-layer control.

SYMBOLS

c_l section lift coefficient

c_d section drag coefficient

α_o section angle of attack, degrees

c airfoil chord, feet

V_o free-stream velocity, feet per second

b model span, feet

Q quantity of air removed through suction slot, cubic feet per second

C_Q flow coefficient $\left(\frac{Q}{V_o c b}\right)$

ν kinematic viscosity, square feet per second

R Reynolds number $\left(\frac{V_o c}{\nu}\right)$

H_o free-stream total pressure, pounds per square foot

H_b total pressure inside wing duct, pounds per square foot

q_o free-stream dynamic pressure, pounds per square foot

C_p pressure coefficient $\left(\frac{H_o - H_b}{q_o}\right)$

δ_f flap deflection, degrees

$c_{l_{max}}$ maximum section lift coefficient

$\Delta c_{l_{max}}$ increase in maximum section lift coefficient

MODEL AND TEST METHODS

The model used in the present tests was a 2-foot-chord laminated-mahogany model of the NACA 65_4-421 airfoil section built to conform to the ordinates presented in table 1. The double slotted flap was comprised of an aluminum-alloy vane and a steel flap for which ordinates are presented in tables 2 and 3, respectively. A diagrammatic sketch that illustrates the general arrangement of the model and shows the double slotted flap in its optimum position is presented as figure 1(a). Photographs of the model with the flap deflected are presented as figures 1(b) and 1(c). For the flap-retracted condition, the vane was retracted into the wing and the flap formed the rear part of the airfoil.

The tests were conducted in the Langley two-dimensional low-turbulence tunnel (reference 3) with the model completely spanning the 3-foot jet. Lift measurements were obtained by integrating the pressures along the floor and ceiling of the tunnel test section and drag was obtained by the wake-survey method. The quantity of air removed through the suction slot was determined by measuring the total and static pressures in the throat of a venturi located in the pipe line between the model and the inlet of the blower used to force air flow through the system. The total pressure inside the wing duct was measured by a flush pressure orifice in the duct at the end opposite to that at which air was removed from the model. For a flow coefficient of zero the plain airfoil was simulated by filling and fairing the suction slot with plasteline.

For tests of the model with the roughened leading edge, carborundum grains were applied with shellac to both surfaces of the airfoil from the leading edge to 0.078c. The carborundum particles had average diameters of 0.011 inch and were spread sparsely to cover 5 to 10 percent of the roughened area.

At the outset of the investigation, various positions and deflections of the vane and flap with respect to one another and to the airfoil were surveyed in order to obtain the configuration producing the greatest maximum lift coefficient. These surveys were made at a flow coefficient of 0.02 and at a Reynolds number of 2.2×10^6. Once the optimum position had been found, the lift characteristics of the model were determined over a range of flow coefficient from 0 to 0.03 and at Reynolds numbers of 1.0×10^6 and 2.2×10^6. The lift and drag characteristics were determined for the same range of Reynolds number and flow coefficient with the flap retracted.

RESULTS AND DISCUSSION

Lift Characteristics

The variations of lift coefficient with angle of attack for the model smooth and with leading-edge roughness and with the flap deflected and retracted are presented in figure 2 for a Reynolds number of 1.0×10^6 and in figure 3 for a Reynolds number of 2.2×10^6. These figures illustrate the following general effects of boundary-layer control upon the lift characteristics: Increasing the flow coefficient increased the maximum lift coefficient and the lift-curve slope and decreased the angle of attack for zero lift. The increase in lift-curve slope and decrease in angle of zero lift are attributed to a thinner boundary layer over the rear part of the airfoil which produced an effect similar to that of increased camber. For the range of flow coefficient investigated, the angle of attack for maximum lift with boundary-layer control and flap deflected and retracted did not exceed by more than 9° – and in most cases was equal to or less than – that of the plain airfoil without boundary-layer control. The increases in maximum lift coefficient resulted for the most part from an extension of the straight part of the lift curve to higher angles of attack with boundary-layer control than those without boundary-layer control.

The effects of Reynolds number and leading-edge roughness on the variation of the maximum section lift coefficient with the flow coefficient are summarized in figure 4. With the flap retracted the maximum lift coefficient continued to show an appreciable increase as the flow coefficient increased throughout the range of flow coefficient investigated; whereas with the flap deflected little increase in the maximum lift coefficient was obtained between flow coefficients of 0.02 and 0.03. In the smooth condition at a Reynolds number of 2.2×10^6 the maximum lift coefficient increased only 0.02 between flow coefficients of 0.015 and 0.030 when the flap was deflected. In general, for the range of flow coefficient investigated, increasing the Reynolds number tended to increase the maximum lift coefficient between flow coefficients of 0 and 0.015 and to decrease the maximum lift coefficient between flow coefficients of 0.015 and 0.030. Leading-edge roughness resulted in large decreases in the maximum lift coefficient throughout the range of flow coefficient investigated.

The increases in the maximum lift coefficient obtained with boundary-layer control at a Reynolds number of 2.2×10^6 are summarized in the following table for the model smooth and with leading-edge roughness:

δ_f (deg)	Model in smooth condition			Model in rough condition		
	$c_{l_{max}}$		$\Delta c_{l_{max}}$	$c_{l_{max}}$		$\Delta c_{l_{max}}$
	$C_Q = 0$	$C_Q = 0.015$		$C_Q = 0$	$C_Q = 0.015$	
0	1.22	2.43	1.21	1.09	1.92	0.83
50.9	3.07	3.81	.74	2.67	3.21	.54

Considerably larger increases in the maximum lift coefficient were obtained with boundary-layer control for the flap-retracted condition than for the flap-deflected condition, and the increases in maximum lift coefficient were less for the rough condition than for the smooth condition. In the smooth condition, increasing the flow coefficient from 0 to 0.015 increased the maximum lift coefficient from 1.22 to 2.43 with the flap retracted and from 3.07 to 3.81 with the flap deflected.

Drag Characteristics

<u>External drag characteristics</u>.- The variations of the section drag coefficient with the section lift coefficient for the model

both smooth and rough with the flap retracted are presented for Reynolds numbers of 1.0×10^6 and 2.2×10^6 in figures 5 and 6, respectively. For all configurations, increasing the flow coefficient brought about large reductions in the minimum drag coefficient and maintained low drag coefficients to very high lift coefficients. The lift coefficient at which the minimum drag coefficient occurred increased as the flow coefficient increased. Leading-edge roughness without boundary-layer control caused the drag coefficients to increase very rapidly at lift coefficients above 0.4. (See figs. 5(b) and 6(b).) These rapid increases are probably caused by separation from the airfoil upper surface. The variations of minimum section drag coefficient with flow coefficient are presented in figure 7 for the model smooth and rough at Reynolds numbers of 1.0×10^6 and 2.2×10^6 for the flap-retracted condition. The effect of Reynolds number on the minimum drag coefficient was small as compared with the effect of boundary-layer control. At a flow coefficient of zero, roughness brought about large increases in minimum drag coefficient, but the difference between the minimum drag coefficients for the rough and smooth conditions decreased rapidly as the flow coefficient increased until at a flow coefficient of 0.03 the minimum drag coefficients were almost identical for both surface conditions and for both Reynolds numbers.

Internal drag characteristics.- The variations of pressure coefficient C_P with angle of attack are presented in figures 8 and 9. The pressure coefficient is a measure of the loss in total pressure in the boundary layer up to the slot and the losses incurred in passing through the slot and in expanding into the duct and is necessary to estimate the power required for boundary-layer control at any lift coefficient and flow coefficient. If the air removed from the boundary layer is assumed to be exhausted at free-stream total pressure, the equivalent drag chargeable to the boundary-layer installation may be expressed in the form

$$\text{Drag} = \frac{(H_o - H_b)Q}{V_o}$$

and the equivalent drag coefficient, therefore, is

$$\frac{Q}{V_o cb} \frac{(H_o - H_b)}{q_o} = C_Q C_P$$

The power required can then be estimated by multiplying the product $C_P C_Q$ by the applicable values of free-stream velocity, dynamic pressure, and wing area.

Although marked reductions in the external drag coefficients measured by the wake surveys were produced by boundary-layer control, computations indicated that the drag coefficients equivalent to the boundary-layer-control power were considerably greater than the reductions obtained, at least over the range of lift coefficient for which the drag was measured without boundary-layer control. The configuration tested therefore does not appear suitable for increasing the effective lift-drag ratio of the airfoil section tested.

CONCLUSIONS

An investigation has been conducted in the Langley two-dimensional low-turbulence tunnel of the NACA 65_4-421 airfoil section with a boundary-layer-control suction slot at 0.45 airfoil chord and a 0.32-airfoil-chord double slotted flap. This investigation has led to the following conclusions:

1. In general, between Reynolds numbers of 1.0×10^6 and 2.2×10^6 and over a range of flow coefficient from 0 to 0.03, increasing the Reynolds number tended to increase the maximum lift coefficient below a flow coefficient of 0.015 and to decrease the maximum lift coefficient between flow coefficients of 0.015 and 0.030.

2. Greater increases in the maximum lift coefficient were obtained through boundary-layer control with the flap retracted than with the flap deflected and with the airfoil in the smooth condition than with the airfoil in the rough condition.

3. In the smooth condition at a Reynolds number of 2.2×10^6, increasing the flow coefficient from 0 to 0.015 increased the maximum lift coefficient from 1.22 to 2.43 with the flap retracted and from 3.07 to 3.81 with the flap deflected. Little increase in maximum lift coefficient for the airfoil with flap deflected was found between flow coefficients of 0.015 and 0.030.

4. With the flap retracted, increasing the flow coefficient decreased the minimum section drag coefficient and maintained low drag coefficients to high lift coefficients. The drag coefficients equivalent to the boundary-layer-control power were greater, however,

than the reduction obtained, at least over the range of lift coefficient for which the drag was measured without boundary-layer control.

Langley Memorial Aeronautical Laboratory
National Advisory Committee for Aeronautics
Langley Field, Va., June 5, 1947

REFERENCES

1. Quinn, John H., Jr.: Tests of the NACA 64_1A212 Airfoil Section with a Slat, a Double Slotted Flap, and Boundary-Layer Control by Suction. NACA TN No. 1293, 1947.

2. Quinn, John H., Jr.: Wind-Tunnel Investigation of Boundary-Layer Control by Suction on the NACA 65_3-418, a = 1.0 Airfoil Section with a 0.29-Airfoil-Chord Double Slotted Flap. NACA TN No. 1071, 1946.

3. von Doenhoff, Albert E., and Abbott, Frank T., Jr.: The Langley Two-Dimensional Low-Turbulence Pressure Tunnel. NACA TN No. 1283, 1947.

TABLE 1

NACA 65_4-421 AIRFOIL SECTION

[Stations and ordinates in percent chord]

Upper surface		Lower surface	
Station	Ordinate	Station	Ordinate
0	0	0	0
.247	1.601	.753	-1.401
.468	1.956	1.032	-1.676
.933	2.493	1.567	-2.065
2.135	3.505	2.865	-2.761
4.583	5.085	5.417	-3.821
7.062	6.329	7.938	-4.633
9.557	7.371	10.443	-5.303
14.575	9.034	15.425	-6.342
19.616	10.304	20.384	-7.120
24.668	11.271	25.332	-7.691
29.729	11.976	30.271	-8.088
34.796	12.433	35.204	-8.313
39.865	12.640	40.135	-8.356
44.934	12.556	45.066	-8.176
50.000	12.158	50.000	-7.746
55.059	11.467	54.941	-7.087
60.108	10.531	59.892	-6.247
65.145	9.419	64.855	-5.299
70.168	8.166	69.832	-4.278
75.176	6.811	74.824	-3.231
80.167	5.388	79.833	-2.204
85.143	3.940	84.857	-1.248
90.104	2.514	89.896	-.446
95.051	1.176	94.949	.088
100.000	0	100.000	0

L.E. radius: 2.50
Slope of radius through L.E.: 0.168

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VANE FOR NACA 65_4–421 AIRFOIL SECTION

[Stations and ordinates in percent airfoil chord]

Upper surface		Lower surface	
Station	Ordinate	Station	Ordinate
0	-0.958	0	-0.958
.625	.708	.625	-2.208
2.000	2.125	1.334	-2.417
2.792	2.625	2.000	-2.250
3.417	3.000	2.729	-1.542
4.792	3.583	3.417	-.042
6.167	3.958	4.792	1.958
7.584	4.167	6.167	3.208
8.959	4.167	7.584	3.792
		8.959	4.167

TABLE 3

FLAP FOR NACA 65_4–421 AIRFOIL SECTION

[Stations and ordinates in percent airfoil chord]

Upper surface		Lower surface	
Station	Ordinate	Station	Ordinate
0	0	0	0
.636	1.625	.636	-1.375
1.375	2.208	1.375	-1.708
2.750	3.042	2.750	-1.958
4.125	3.542	4.125	-1.958
6.916	3.958	8.440	-1.248
8.291	3.875	13.479	-.446
13.687	2.514	18.532	.088
18.634	1.176	23.538	0
23.583	0		

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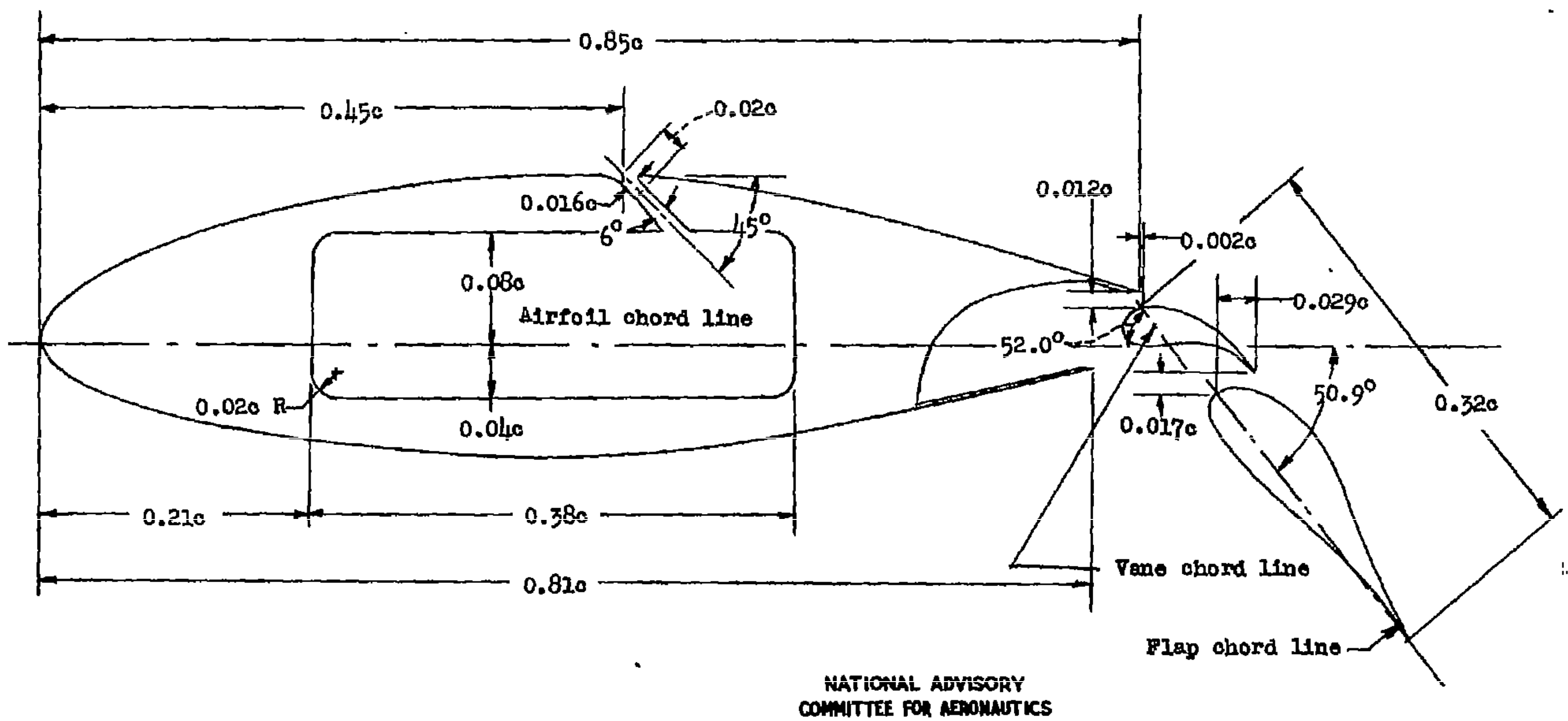
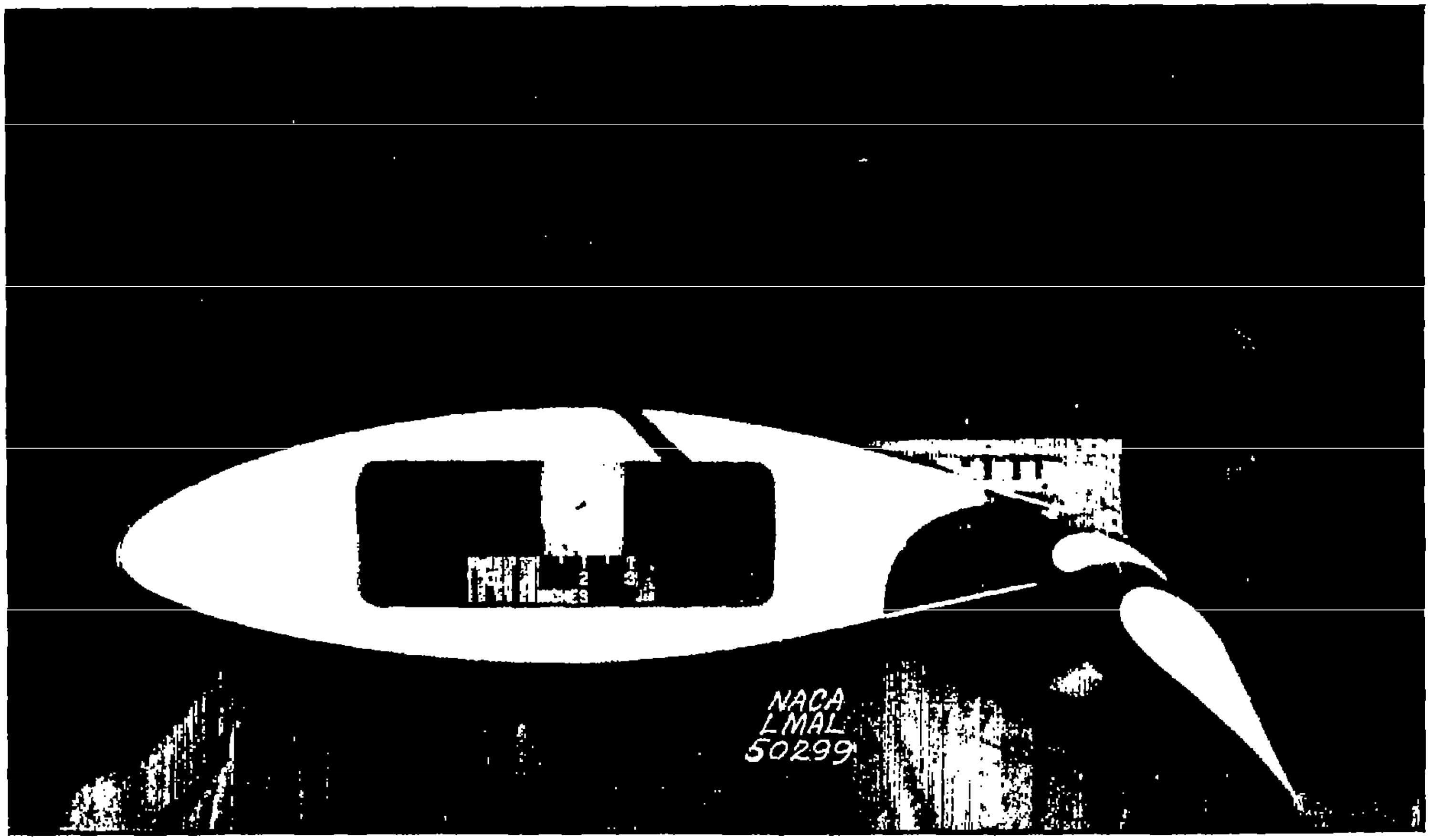


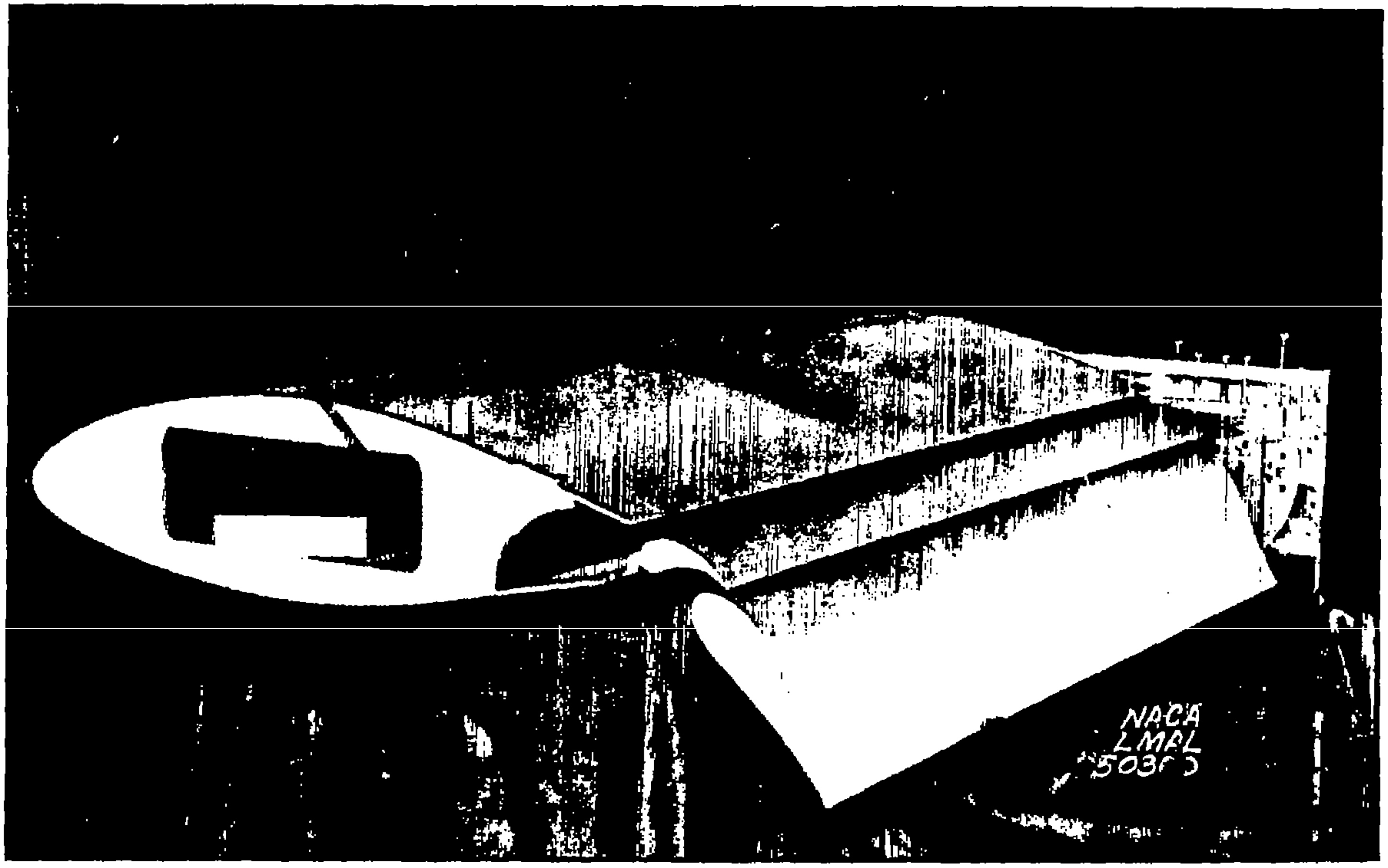
(a) Model dimensions and arrangement showing optimum flap position.

Figure 1.- NACA 65_4-421 airfoil section with double slotted flap and boundary-layer suction slot.



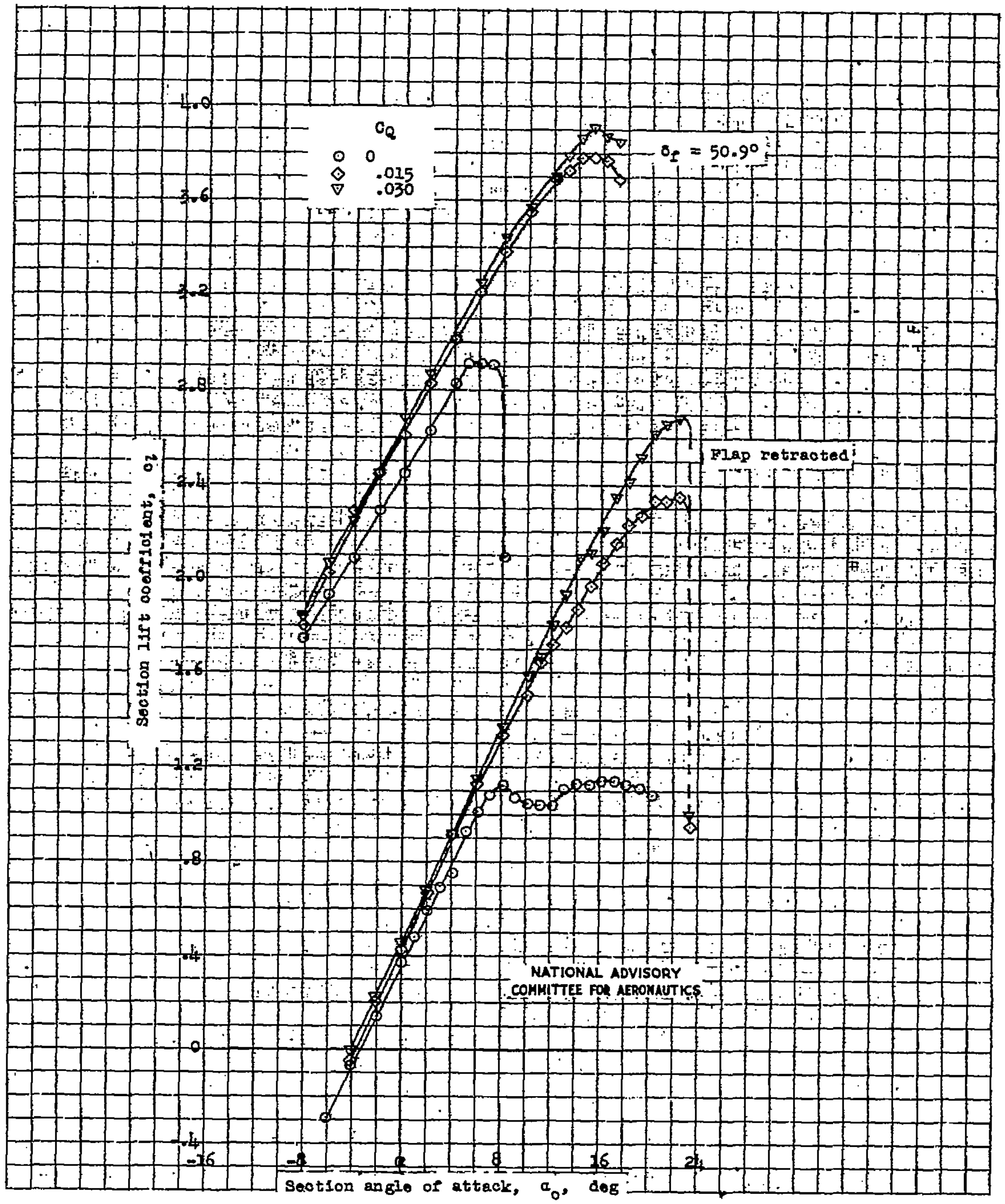
(b) End view of model.

Figure 1.- Continued.



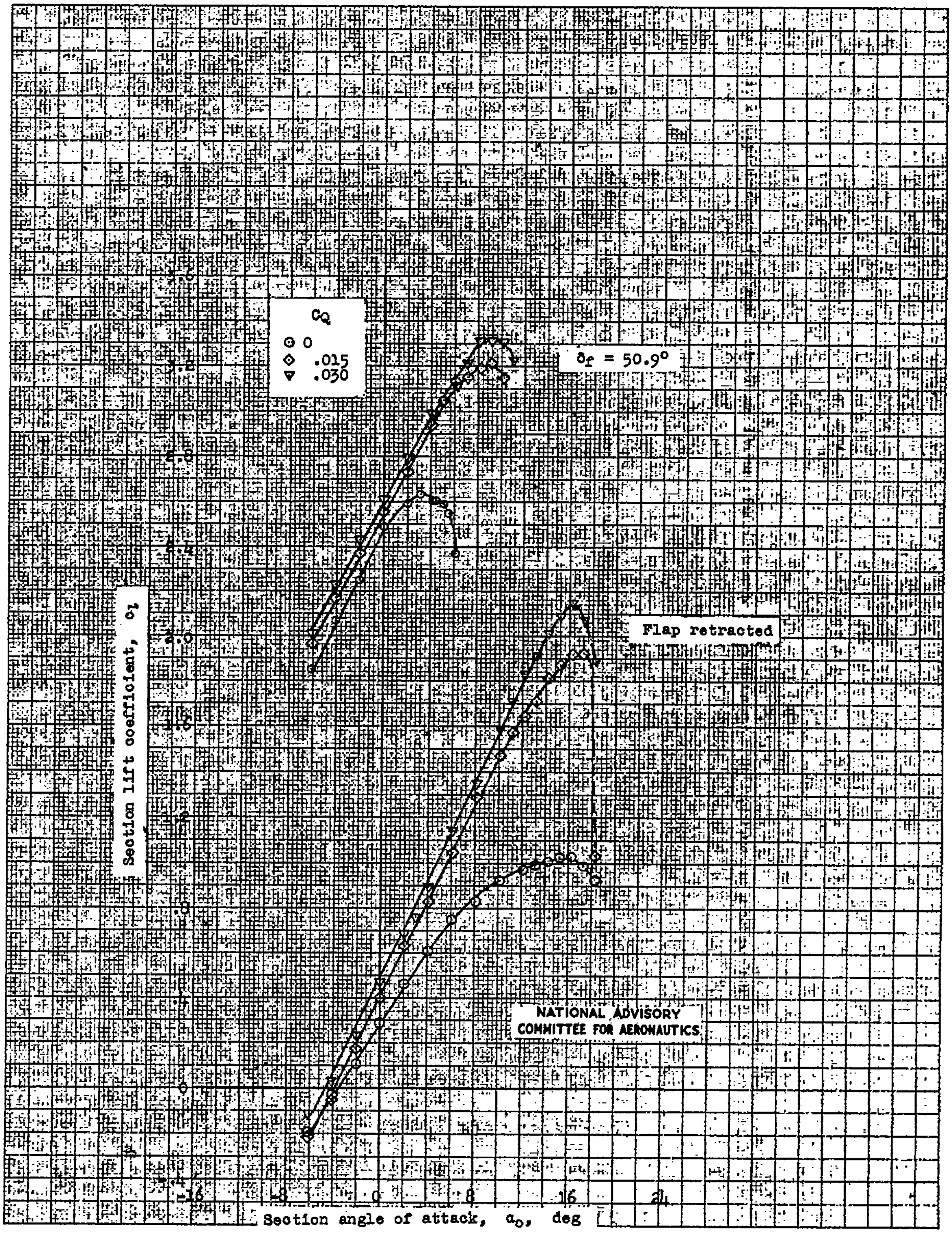
(c) Three-quarter rear view of model.

Figure 1.- Concluded.



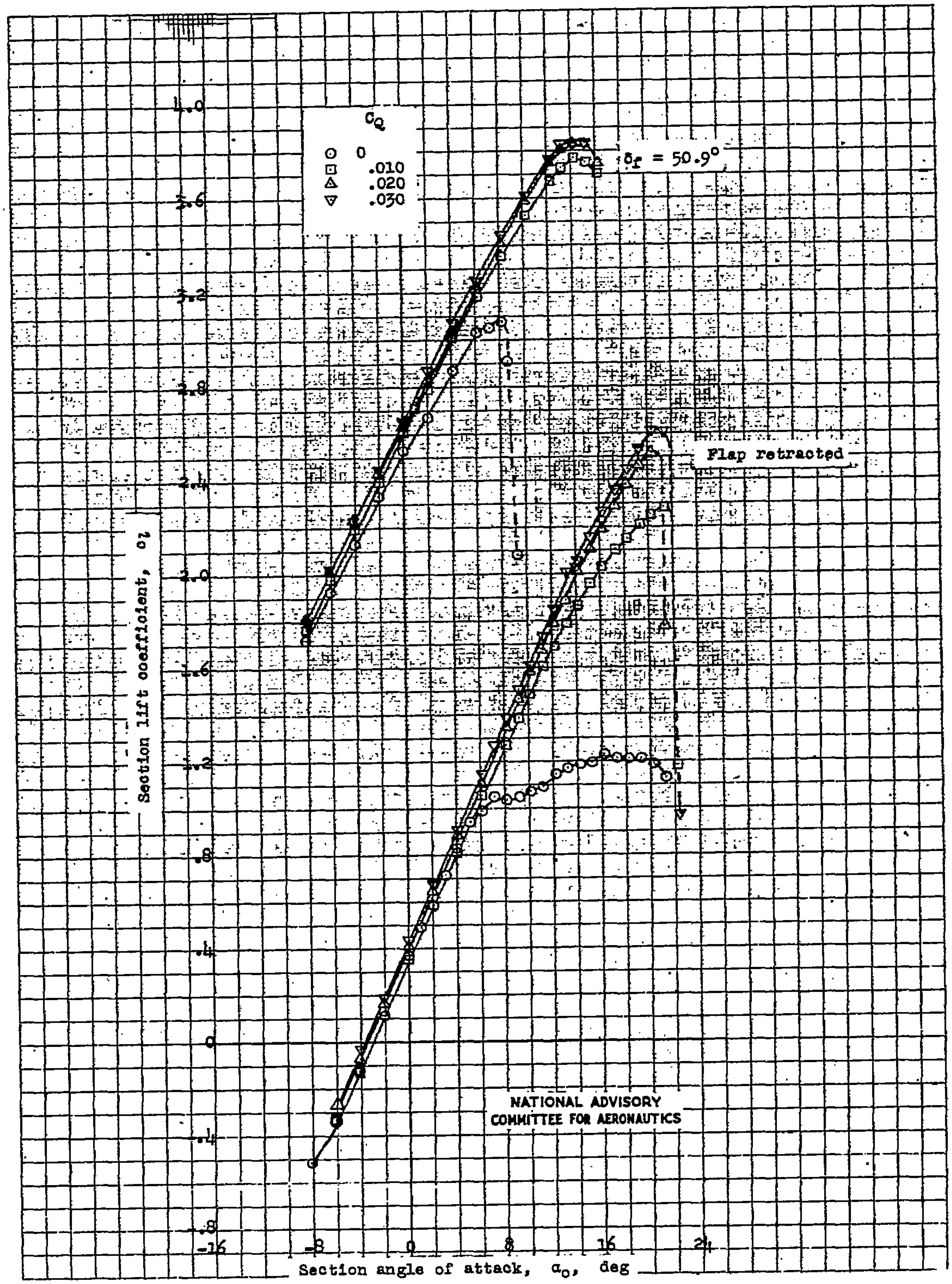
(a) Smooth condition.

Figure 2.- Variation of lift coefficient with angle of attack for NACA 65_4-421 airfoil section with boundary-layer control. $R = 1.0 \times 10^6$.



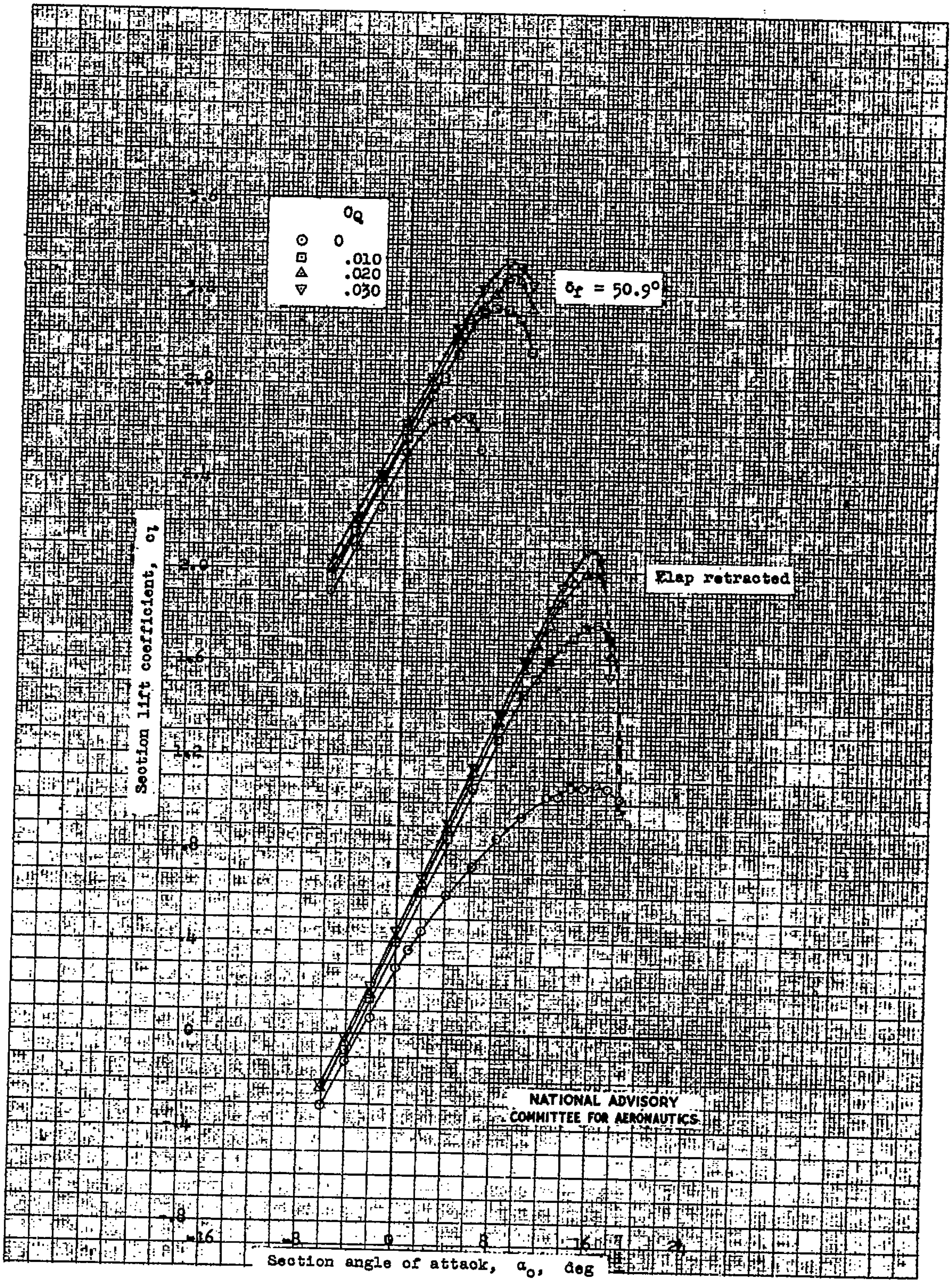
(b) Rough condition.

Figure 2.- Concluded.



(a) Smooth condition.

Figure 3.- Variation of lift coefficient with angle of attack for NACA 65_4-421 airfoil section with boundary-layer control. $R = 2.2 \times 10^6$.



(b) Rough condition.

Figure 3.- Concluded.

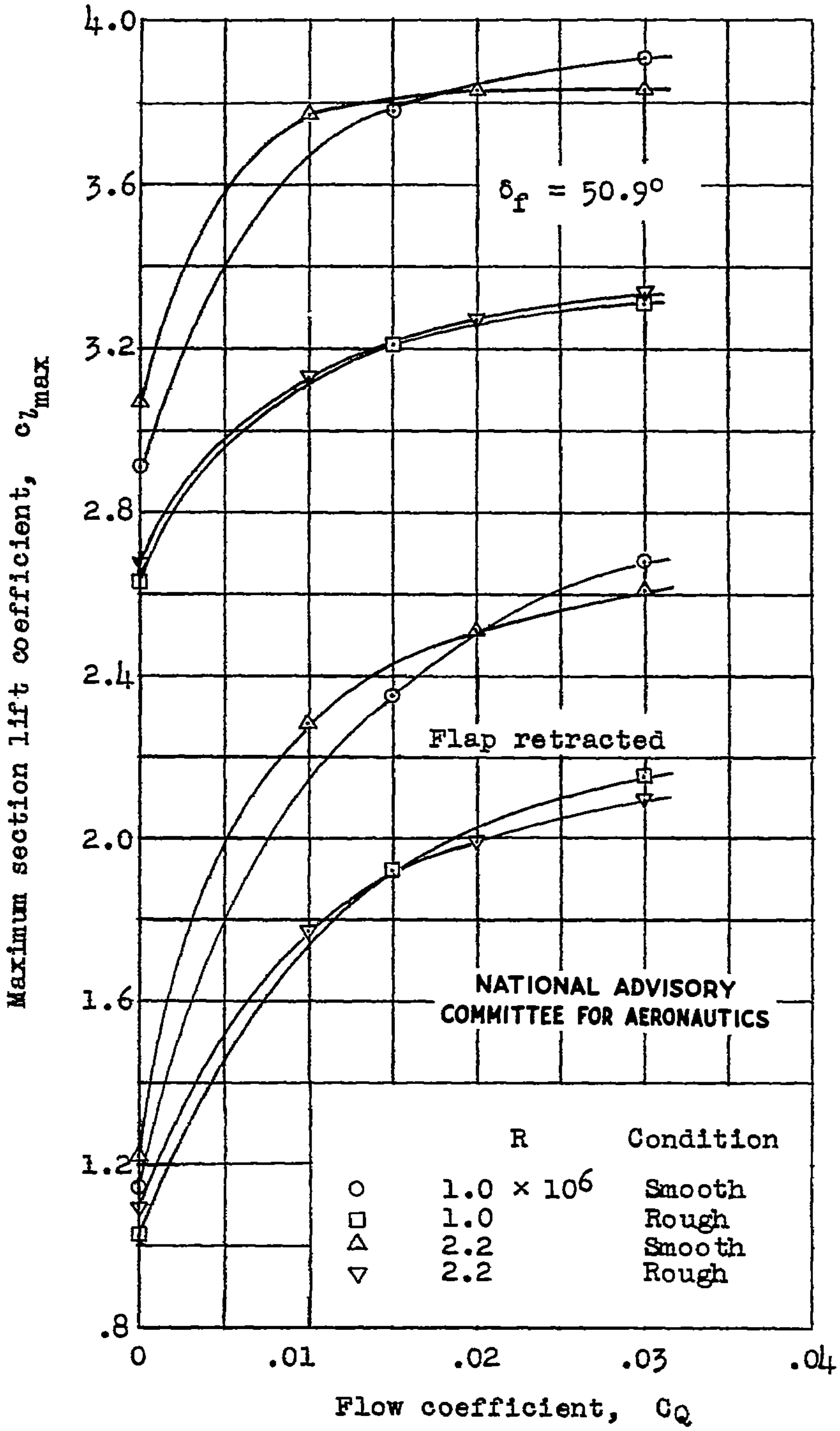
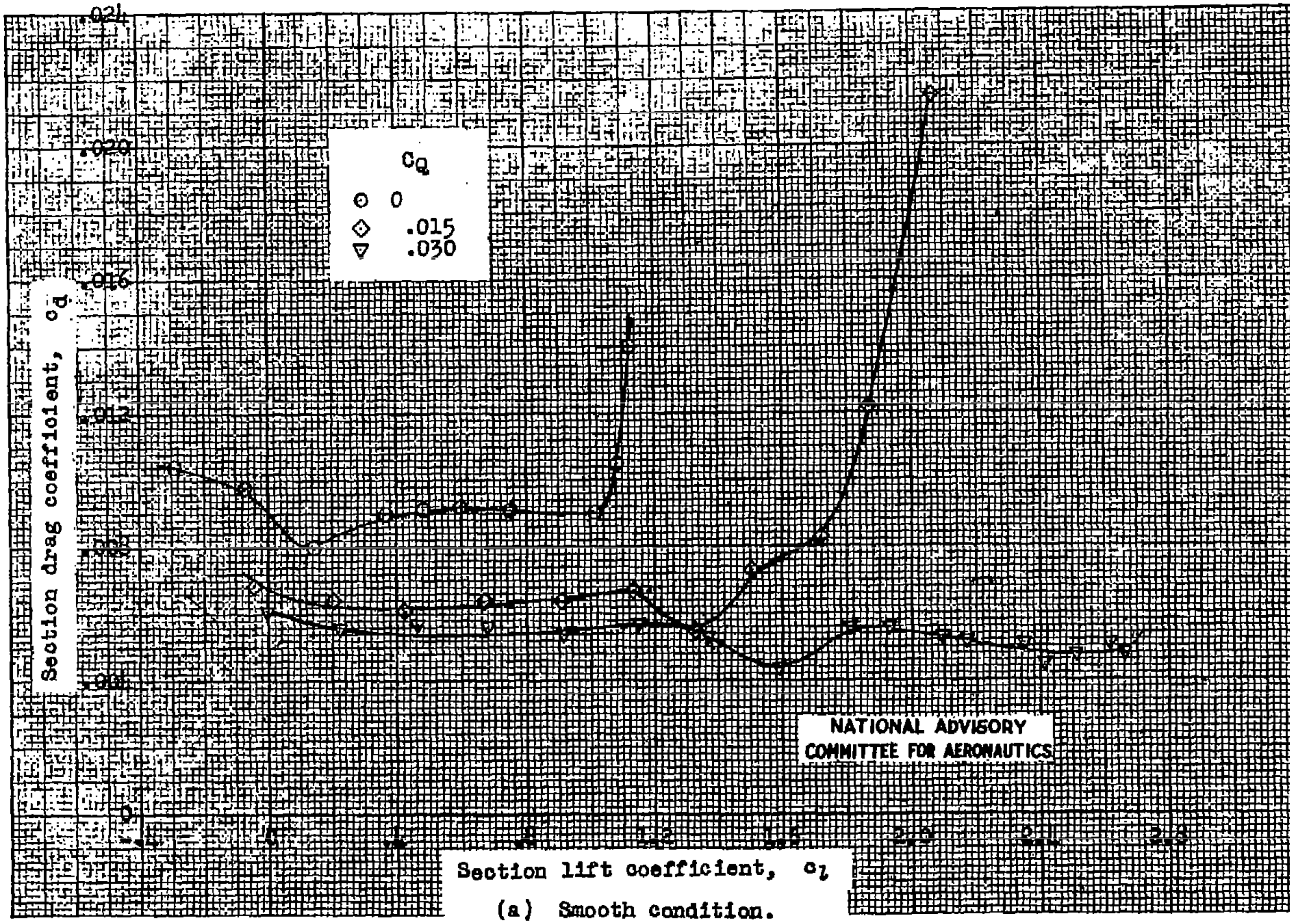
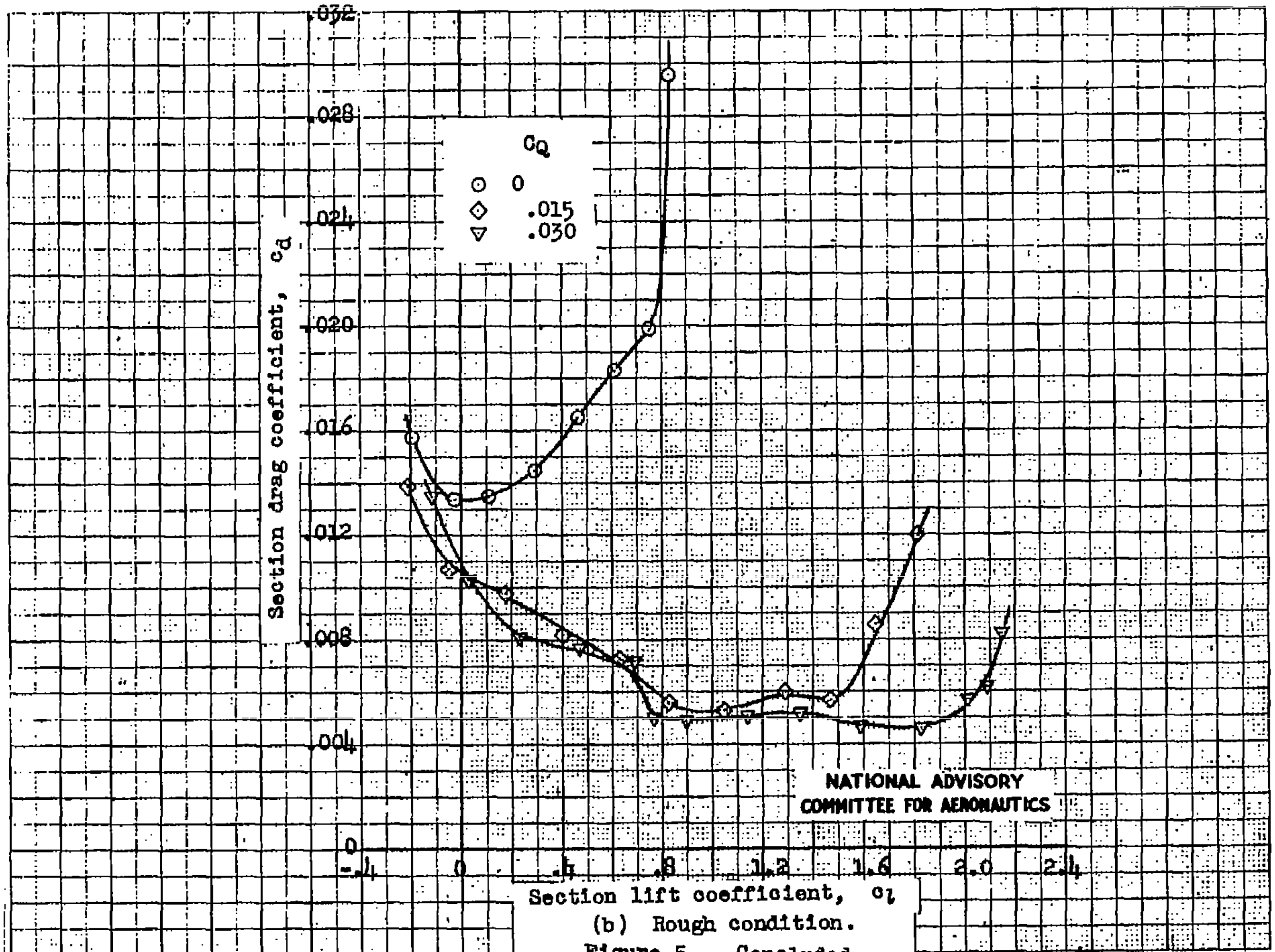


Figure 4.- Variation of maximum section lift coefficient with flow coefficient for NACA 65_4-421 airfoil section with flap retracted and deflected for both smooth and rough conditions.



(a) Smooth condition.

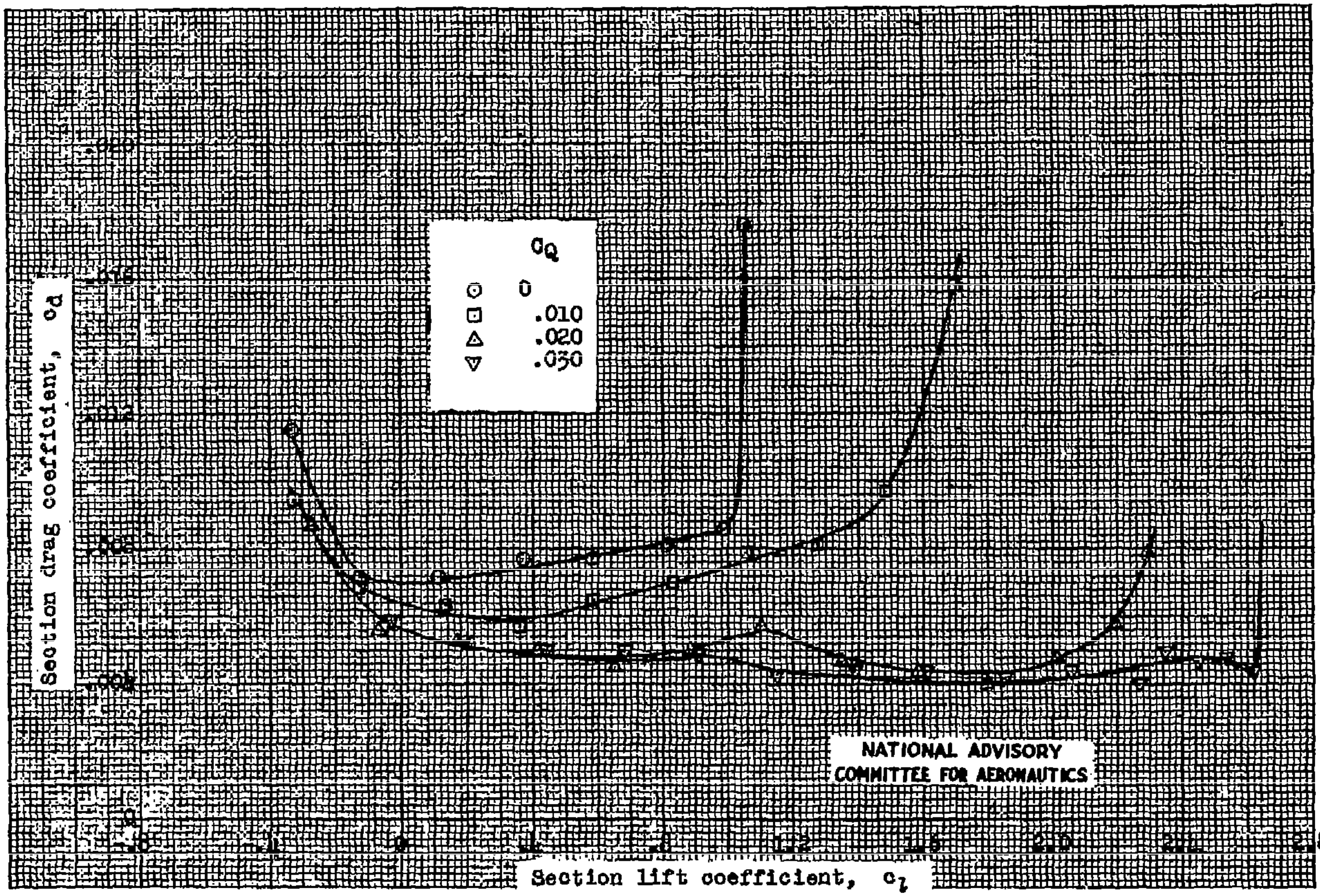
Figure 5.- Drag characteristics of NACA 65_4-421 airfoil section with boundary-layer control. Flap retracted; $R = 1.0 \times 10^6$.



Section lift coefficient, c_l

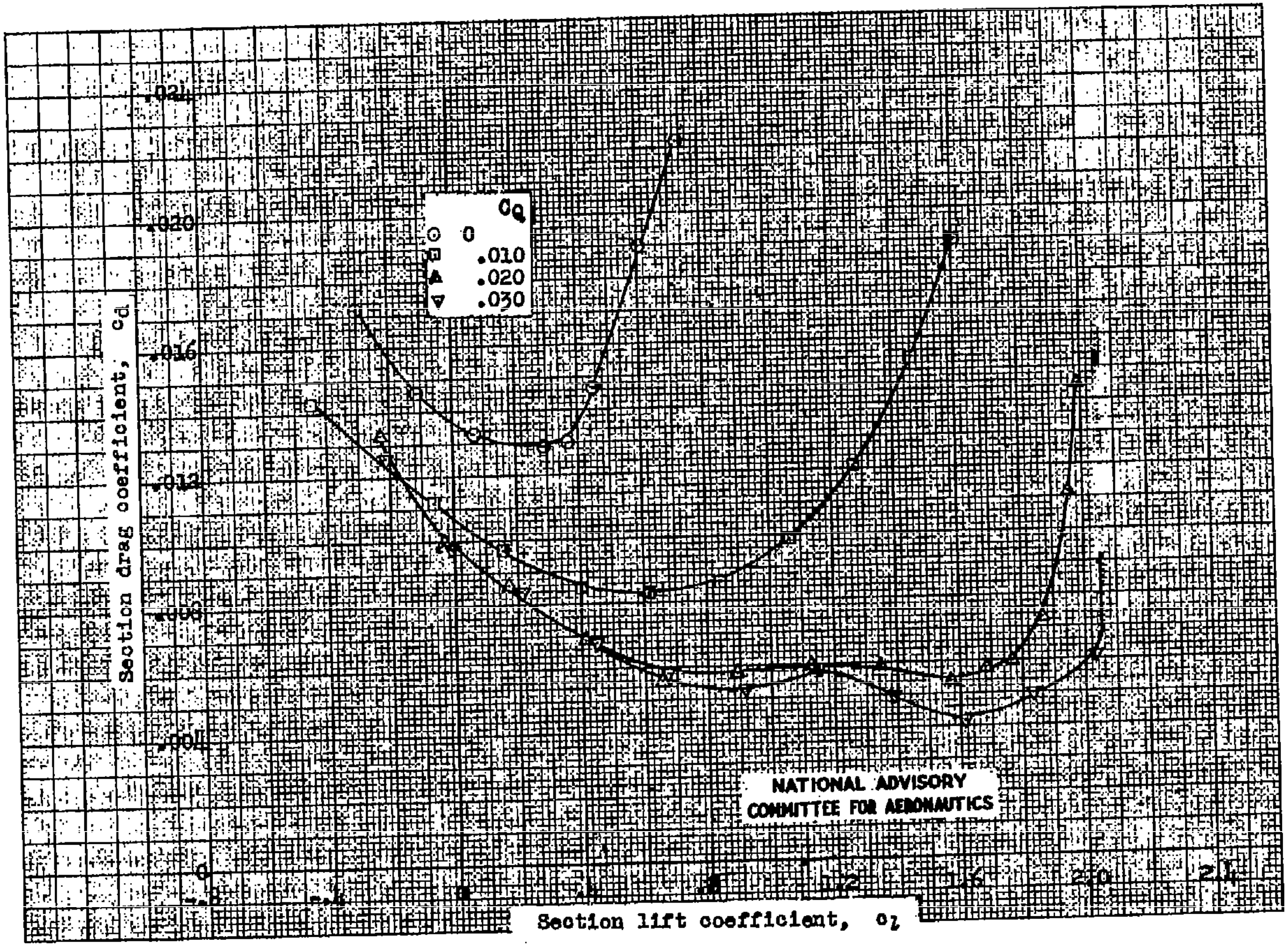
(b) Rough condition.

Figure 5.- Concluded.



(a) Smooth condition.

Figure 6.- Drag characteristics of NACA 65_4-421 airfoil section with boundary-layer control. Flap retracted; $R = 2.2 \times 10^6$.



(b) Rough condition.

Figure 6.- Concluded.

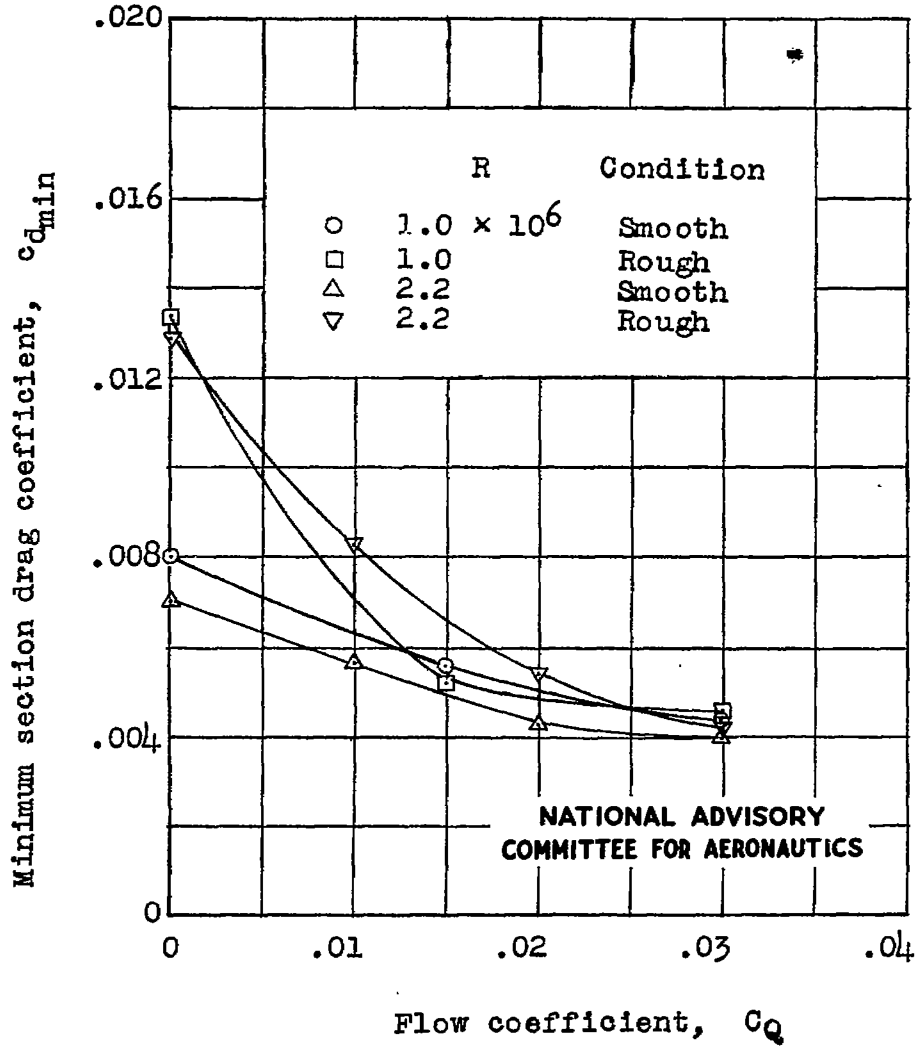
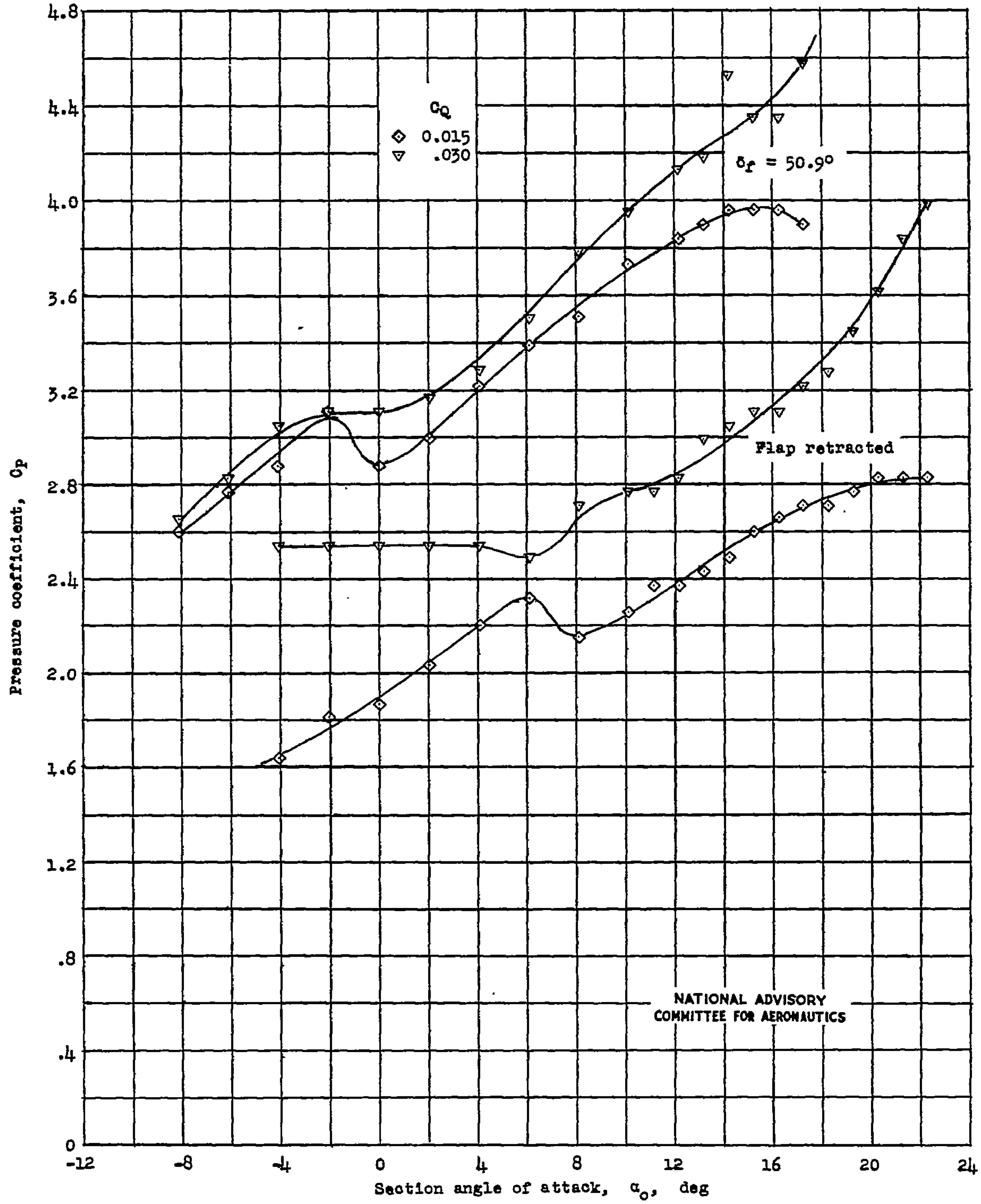
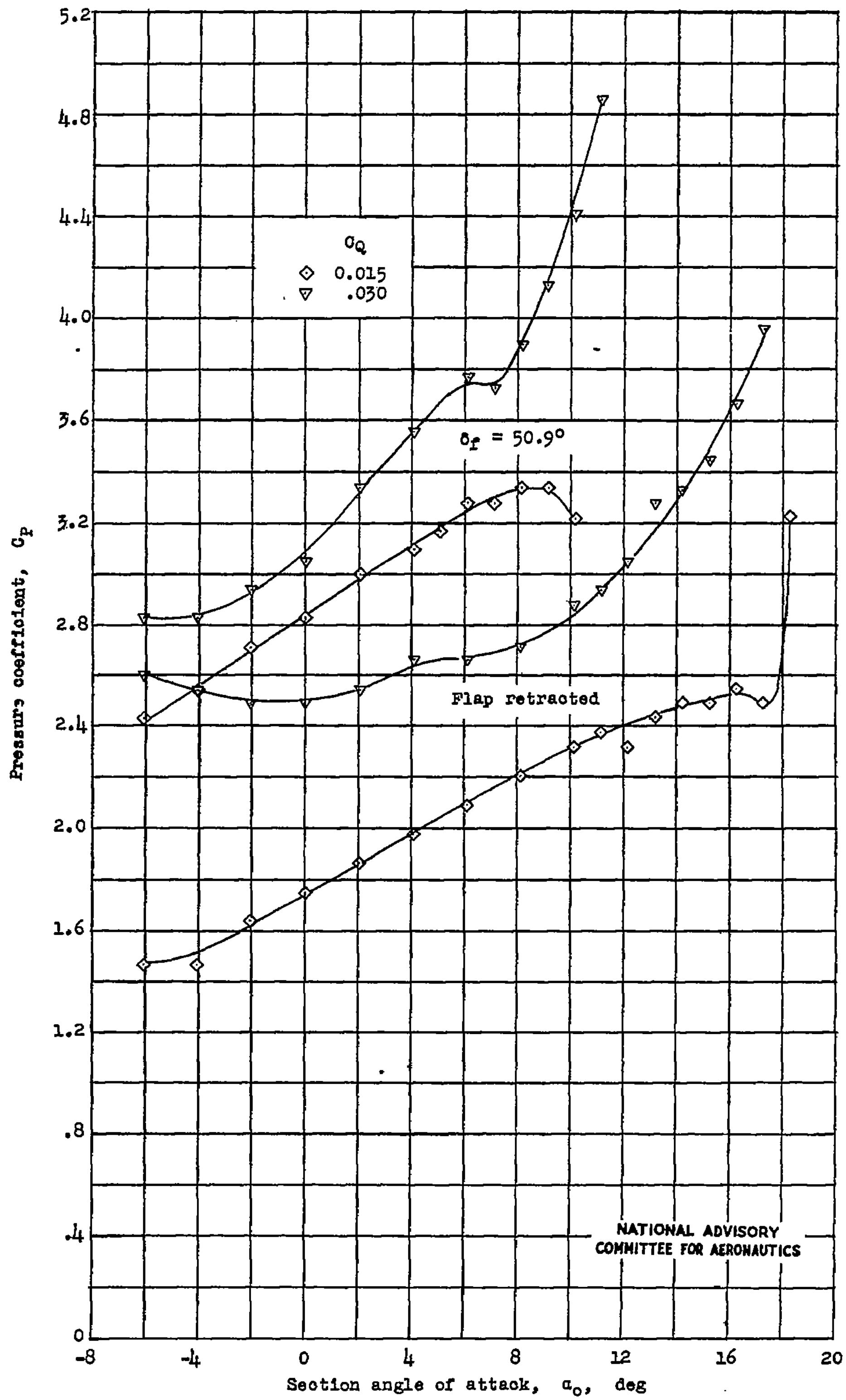


Figure 7.- Variation of minimum section drag coefficient with flow coefficient for NACA 65_4-421 airfoil section smooth and rough. Flap retracted.



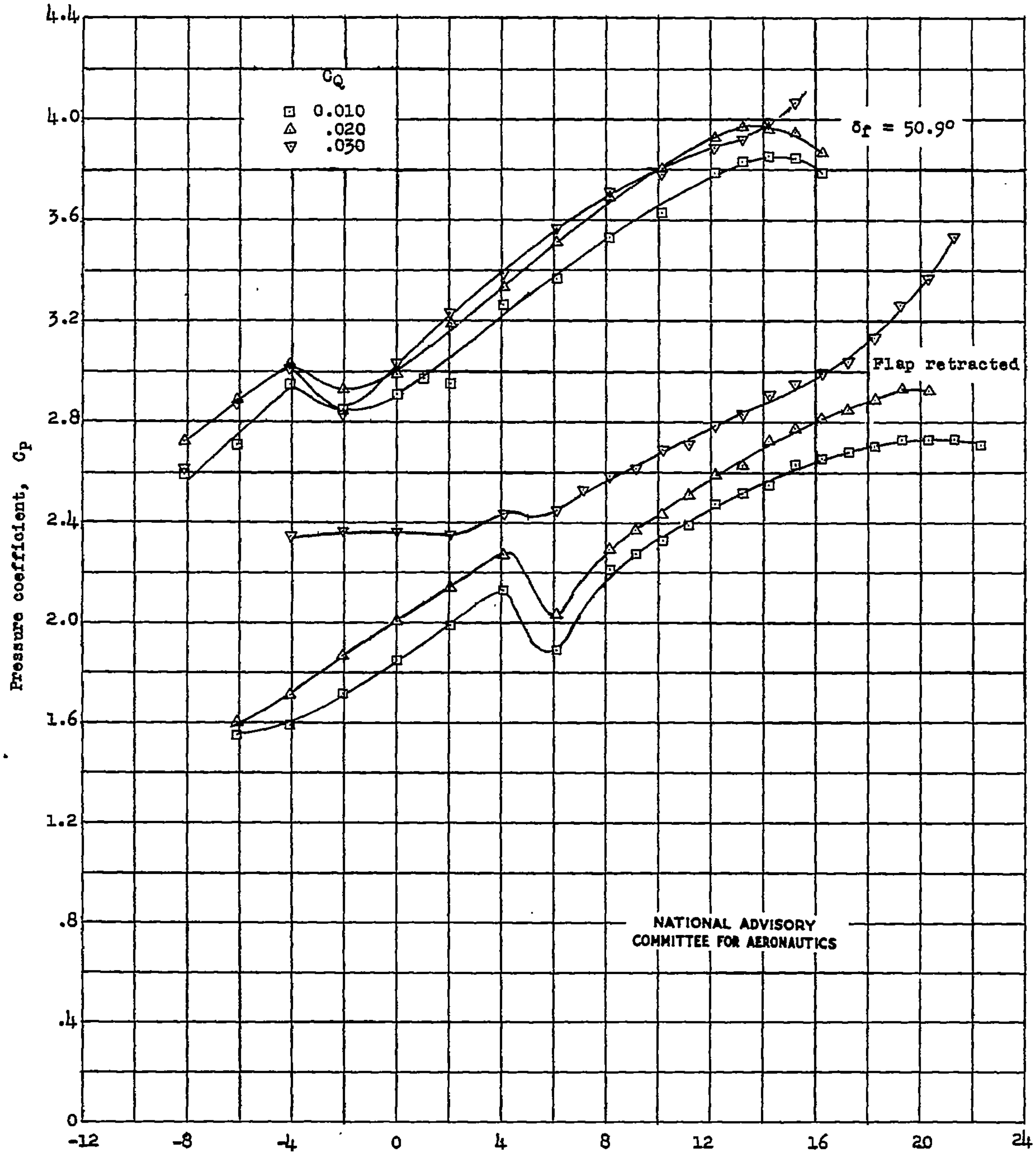
(a) Smooth condition.

Figure 8.- Variation of pressure coefficient with angle of attack for NACA 65_4-421 airfoil section with boundary-layer control. $R = 1.0 \times 10^6$.



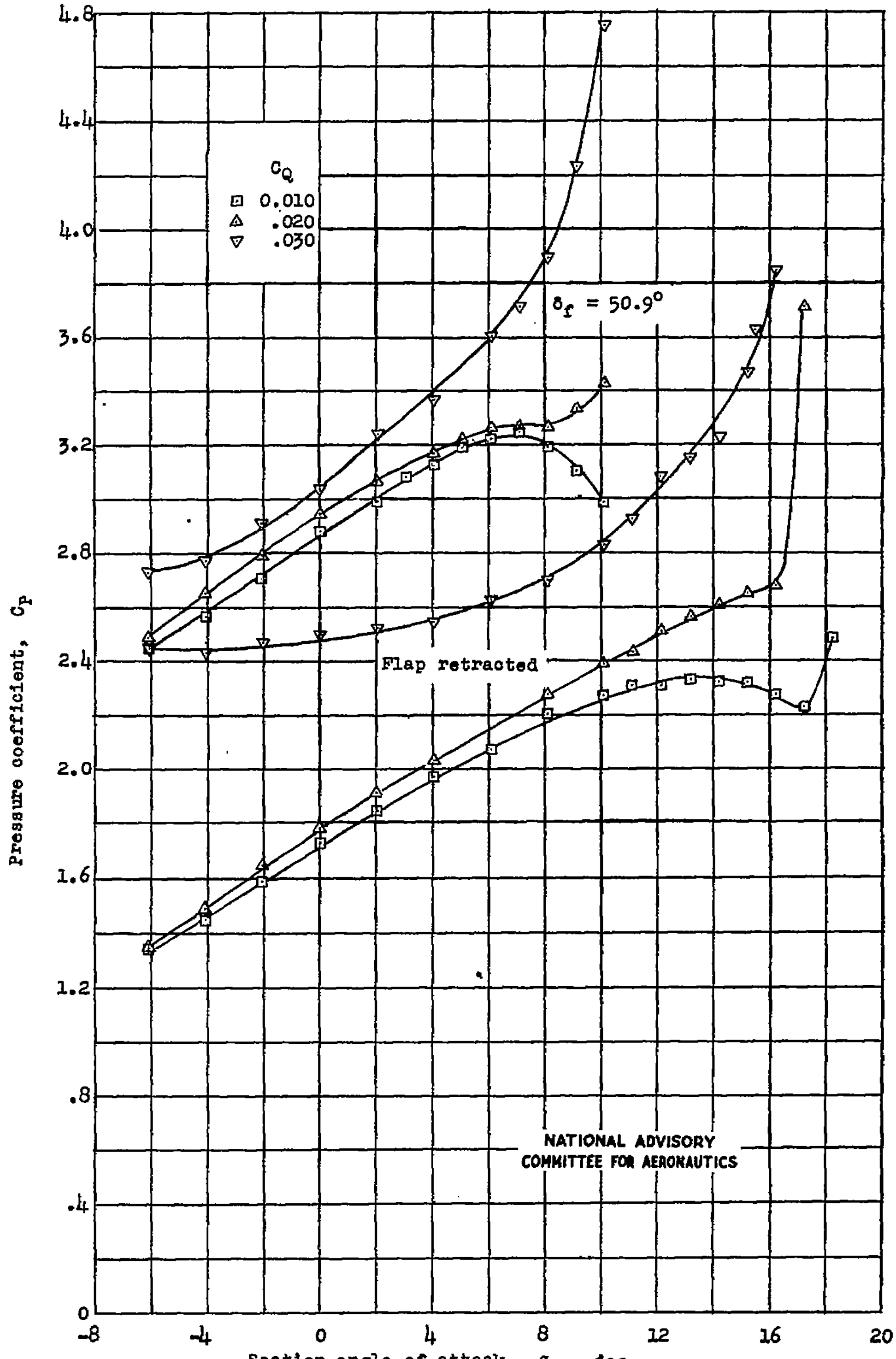
(b) Rough condition.

Figure 8.- Concluded.



(a) Smooth condition.

Figure 9.- Variation of pressure coefficient with angle of attack for NACA 65_4-421 airfoil section with boundary-layer control. $R = 2.2 \times 10^6$.



(b) Rough condition.

Figure 9.- Concluded.